

FLIGHT TEST OF THE ENGINE FUEL SCHEDULES OF THE X-43A HYPER-X RESEARCH VEHICLES

Summary

The Hyper-X program flew two X-43A Hyper-X Research Vehicles (HXRVs) in 2004, referred to as Ship 2 and Ship 3. The scramjet engine of the X-43A research vehicle was autonomously controlled in flight to track a predetermined fueling schedule. Ship 2 flew at approximately Mach 7 and Ship 3 flew at approximately Mach 10.

Objective

The objective of the flight test was to control the fuel equivalence ratio of the scramjet engine. If not controlled properly, scramjets are prone to two unfavorable phenomena: unstarts and flameouts. The primary control is fuel equivalence ratio (ϕ_e), defined as the actual fuel-to-air ratio divided by the stoichiometric fuel-to-air ratio. Flameouts can occur with low fuel equivalence ratios (fuel lean) and unstarts tend to occur with high fuel equivalence ratios (fuel rich). Between these two limits, increasing fuel equivalence ratios generally tends to generate increased engine thrust. Flameouts and unstarts result in the immediate loss of thrust from the scramjet engine and the subsequent deceleration of the scramjet-powered vehicle. Therefore, the control of the fuel equivalence ratio of scramjet engines is crucial to the overall performance of scramjet-powered vehicles.

Approach

There were separate fuel schedules for each vehicle. The fuel schedule was used to ensure correct delivery of fuel to maintain an adequate fuel-to-air ratio in the engine. The equivalence ratio was varied during the time of engine operation to increase the probability of proper ignition and positive acceleration as well as to decrease the probability of engine unstart. The fuel used for the X-43A was hydrogen gas. A gas mixture (80:20 by volume) was used as an igniter that consisted of hydrogen and a pyrophoric gas, silane, which ignites on contact with air. The fueling schedule includes the injection of the igniter gas.

Figure 1 shows the Mach 7 flight fuel schedule and the silane mole fraction of the igniter mixture. The Mach 7 fuel schedule was developed during wind tunnel testing in the NASA Langley Research Center 8-Foot High Temperature Tunnel (refs. 1 and 2). This fueling profile was a compromise between desired fueling test points, fueling transitions, and hardware capabilities. For example, step inputs during ignition were required because of an undesirable low flow rate condition of the pressure regulators (ref. 3). This fueling profile resulted in three stable fueling instances or plateaus, with a ϕ_e of 0.75 (with igniter), 0.9 (hydrogen only) and with a goal value of 1.3 (hydrogen only). This same fueling profile also allowed slow transitions between stable fueling instances to reduce the risk of an engine-out condition. Further risk reduction for unstarts was accomplished through a set of unstart protection algorithms, which became active only above a ϕ_e of 0.9.

Figure 2 shows the fuel schedule for the Mach 10 flight, which did not include lean fueling ϕ_e plateaus (excluding ignition). This omission was made to match wind tunnel test points and to expedite the fuel schedule to the more important rich ϕ_e data points, where positive vehicle acceleration was more probable. The lean fueling data (without igniter below ϕ_e of 1.0) was placed at the end of the schedule because of the risk of flameout at low ϕ_e values. A number of tests at the NASA HYPERSONIC PULSE (HYPULSE) Facility located at and operated by the GASL Division of Allied Aerospace Industries, Inc., Ronkonkoma, New York, were performed to anchor the analysis tools for the scramjet engine (refs. 4 and 5).

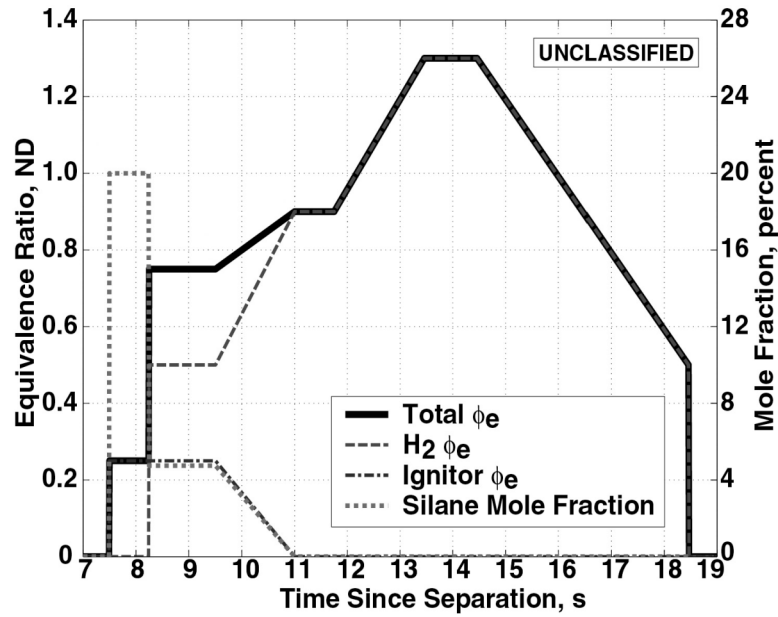


Figure 1. Mach 7 fuel schedule.

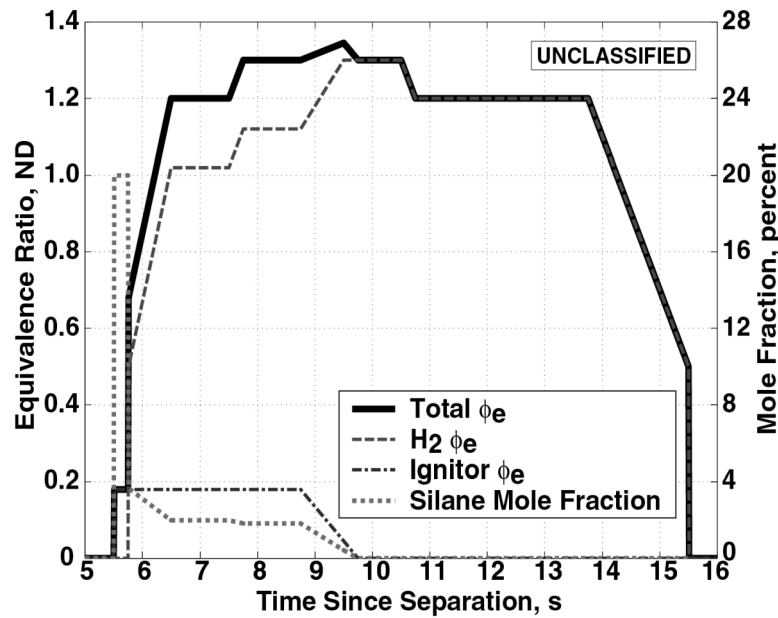


Figure 2. Mach 10 fuel schedule.

Results

The fuel schedules described above were implemented into the propulsion system controllers (PSCs) for the Mach 7 and Mach 10 flight tests. Rock (ref. 6) provides a discussion of the development and testing of the PSC, and Jones and Baumann (ref. 7) discuss further software testing and validation using a Monte Carlo technique with a six degree-of-freedom batch simulation. Although the details of the engine performance are classified, the PSC did adequately control the engine along the predetermined fuel schedules for both Ship 2 and Ship 3 without an unstart or flameout event. The installed engine performance was within

preflight predictions for both flights. Jones et al. (ref. 8) give a summary of the PSC performance.

Status and Future Work

Shortly following the flight of X-43A Ship 3, the project was ended and all follow-on projects, such as X-43B and X-43C, were terminated. The United States Air Force, however, is going forward with their flight program, a scramjet engine demonstrator. Further research is required, however, to progress the scramjet engine technology. More flight tests of unstart protection algorithms are needed to provide a better understanding of the unstart phenomenon. Flight test of hydrocarbon-fueled engines to evaluate the performance differences with hydrogen is also needed. The ramjet to scramjet transition needs study to evaluate transition combustion stability. Flight test at unsteady test points (over Mach and q_{bar}) is required to evaluate real life engine operability. Many of these tasks can and should be performed using small scale flight tests with a high flight rate. This would help drive the technology and reduce the cost of testing.

References

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Contacts

Thomas Jones, DFRC, Code RP, Thomas.P.Jones@nasa.gov